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by John Dimeff, Keith McFarland, Inder N. Chabra, and Edward L. Conley

Ames Research Center
Moffett Field, Calif.

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SUMMARY

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A new type of internal-sting, six-component, strain-gage balance has been developed and calibrated at Ames Research Center. The balance is used to measure the aerodynamic forces on wind-tunnel test models.

A unique feature of the balance is a hollow cavity running the length of the balance, through which additional wires, linkages, hydraulic lines, etc., can be passed. Other attractive features include the ease of alining the force elements, and the ability to fabricate the assembly with standard machine shop tooling. These features are made possible by the relatively simple geometry with all elements being machined in one piece.

The performance of the balance is comparable to that of the best commercial balances available.

author

INTRODUCTION

Sting balances internally support the model in the wind tunnel and measure the aerodynamic forces on the model by means of strain-gaged links located within the model. The various sting balances are categorized according to the arrangement of their measuring elements. Two common arrangements of elements are: first, a "floating-frame" geometry in which forces are transmitted from model to ground support through a number of elements in parallel; and second, a "compound" geometry in which forces are transmitted from model to ground support through a number of elements arranged in a series-parallel configuration.

Common balance configurations have provided aerodynamic test programs at the Ames Research Center with a wide range of characteristics. However, disadvantages of these balances have sometimes limited their usefulness. To eliminate some of the restricting disadvantages, a modified version of the floating-frame balance has been developed. This new balance has been called a "two-plane" balance because all the force measuring elements are located in one or the other of two cross-sectional planes near the front and aft ends of the balance, respectively.

In this report the advantages and disadvantages of current types of balances are discussed, and the design and performance of the two-plane balance are described.

CHARACTERISTICS OF CURRENT TYPES OF BALANCES

Floating-frame balances (fig. 1) generally consist of an outer cylindrical sleeve attached by means of the measuring elements to an inner rod. The inner rod is attached to the sting, while the outer sleeve supports the model. Six measuring elements are used, each designed to measure one force component. Two vertical elements located forward and aft resolve normal force and pitching moment. Two similarly spaced horizontal elements measure side force and yawing moment. An axially oriented element measures the axial force and a concentric torque tube measures the rolling moment. Each element is isolated from the remaining force components in the force system by the pivot action of flexures.

Advantages of this type of balance over the compound type balance are:

(1) A greater percentage of the load component is transmitted through the element designed to measure that component because of the high compliance of the flexures.

(2) High rigidity minimizes clearance interference problems.

(3) Interactions are low, reducing calibration time and effort.

(4) Design can be varied to accommodate a large range of load capacities for any physical size.

(5) Any element can be replaced, in the event of failure, without incapacitating the entire balance.

Disadvantages of this type are:

(1) Alinement of measuring elements during assembly requires very close tolerances.

(2) Repairs are difficult, requiring considerable expense and time.

(3) Design problems are complicated by limited stiffness of fastenings, outer sleeves, etc.

(4) Internal space is so thoroughly filled by the elements and their attachments that there is little room for additional wiring for special model instrumentation.

(5) Dual slopes resulting from positive and negative loadings necessitate additional data reduction.

In the compound balances (fig. 2) the axial force is measured in a separate section through which all other forces must be transmitted. The other elements for measuring forces or moments are arranged in a "cage" located aft of the axial element, or in a pair of cages located fore and aft of the axial element. Some advantages of compound balances are:

.(1) They are less expensive than the floating-frame type because of their simpler design and greater ease of fabrication.

(2) They can be smaller and accommodate lower capacities.

(3) They can accommodate lower force ranges or lower ratio of axial to normal force.

Compound balances have two rather serious disadvantages:

(1) Because they are not very stiff, there is a possibility of fouling between the model and the balance if adequate clearances are not provided for.

(2) Large first- and second-order interactions require multiple load calibration for evaluating calibration constants.

The Two-Plane Balance

Description.- The two-plane balance (figs. 3-5) consists of an outer sleeve attached at its extremities to an inner hollow-center cylindrical rod. The rod is attached to the sting, while the central portion of the outer sleeve supports the model. The loads on the outer sleeve are transmitted to the inner rod through eight measuring links symmetrically arranged in two parallel planes perpendicular to the longitudinal axis and gaged to measure the six aerodynamic force and moment components. The design utilizes column-type elements for all forces and moments except axial forces (figs. 4 and 5). The links are arranged so that a normal force places one pair of diagonally opposite vertical links (e.g., front right and rear left) in tension and the second pair in compression. Side force is measured by a second set of four links. Rolling moment is measured from the column-type stresses induced in the same elements as the normal and side forces, while axial force is measured from the fixed beam stresses in these links.

Based on this design concept, a 2-1/2-inch-diameter two-plane balance has been constructed and evaluated for the following loads:

Front normal and rear normal force (N_F,N_A)	1000 lb each
Front side and rear side force (S_F,S_A)	1000 lb each
Axial force (A)	300 lb each
Rolling moment (R)	2000 in.-lb

This balance is approximately 13-1/4 inches in overall length. It consists of a 2.5-inch o.d. outer sleeve, 10 inches long, attached at its two extremities by means of pins to an inner hollow cylindrical support approximately 1-3/4-inches o.d. and 1-inch i.d. The two planes containing the measuring links are 8 inches apart and perpendicular to the longitudinal axis of the balance. The links are each 0.13 inch square by 0.75 inch long, and are formed by cutting slots in the outer sleeve close to the sections where it is attached to the

inner support. Deflections of these links under full-scale loads (of the order of 0.0008 inch) are approximately one-half those of the links used in good commercial balances of similar load ratings. The outer sleeve is sufficiently rigid that balance performance does not depend on stiffness supplied by the model. The model is attached to the outer sleeve of the balance by means of dowel pins.

Thermal effects are minimized because all elements are an integral part of the outer sleeve and are, therefore, uniformly influenced by the sleeve temperature. Thermal effects on the axial force are particularly small because any differential expansion between the inner and outer sleeve exerts compensating equal and opposite effects on the axial-force gages in the two measuring planes.

A developed view of the cylindrical outer sleeve is shown in figure 4. The links which transmit the applied forces from the central portion of the outer sleeve to the supported ends are marked 1 to 8. The interconnecting slots are arranged so that positive (upward) normal forces place normal-force links 1 and 7 in tension while links 3 and 5 are in compression (see figs. 4 and 5). Similarly, under the action of positive side forces, links 2 and 8 are in tension while links 4 and 6 are in compression. Normal force, side force, and rolling moment induce column-type stresses in the links, whereas axial force causes bending stresses of the links as fixed beams. Correct positioning of the gages on the columns is critical if interactions are to be kept small. The normal-force, side-force, and rolling-moment gages are placed on the neutral axis of the column to avoid interaction effects produced by the moment distribution when axial force is applied. Since normal and side forces produce the same effects in adjacent arms of the axial-force bridge, these effects on the axial force are cancelled.

The measuring elements have been designed to provide a safety factor of two or more under combined simultaneous maximum loading based on the yield strength of 17-4PH stainless steel of which the balance is made. Stresses introduced by the individual loads are as follows:

Maximum normal stress	28,500 psi
Maximum side stress	18,400 psi
Maximum axial stress	38,400 psi
Rolling-moment stress	14,800 psi

Strains resulting from the above individual stresses are of the order of 500 to 1300 microinches per inch.

Each of the normal- and side-force components is measured by a single four-element bridge, whereas the axial force and rolling moment are each measured by two sets of four-element bridges, one on the forward and the other on the aft measuring links. This arrangement provides higher accuracy in the presence of thermal stresses. Temperature compensated "Constantan" metal-foil gages (0.125 in. L × 0.085 in. W) with fiber glass backing originally installed

in the balance have been satisfactory, although a wide selection of superior gages has been made available on the market since then. Gage installation and curing cycles were in conformance to the manufacturer's recommended procedures with particular emphasis on cleanliness of gage surfaces and alinement of gages. The leads from the strain gages are brought to a Teflon terminal block at the forward end of the balance for wiring connections. Leads from these terminals along with any additional leads from the model are brought to the recording equipment through the hollow inner support and the sting.

Performance.- For purposes of calibration, the balance was installed in a precisely machined calibration sleeve and secured to the central load block of the Ames standard calibration rig. The rig was designed to maintain zero displacement of the balance while loads were applied by means of accurate weights. Forces introduced by the weights were multiplied by stabilized beams and bell cranks, and applied to the balance through struts, isolated from bending loads by flexures. During operation of the rig, a hydraulic servo repositioning system senses any deflections of the load block under the applied loads and restores it to its original position so that the loading struts are always orthogonally oriented to the balance. The output of the balance was monitored by an indicating millivolt potentiometer which was developed at Ames. It is a self-balancing servo amplifier with a 2000-count indicator dial and sufficient torque to drive the shaft-rotation digitizers that are used to provide digital data for entry into automatic processing equipment.

Calibration data indicate an essentially linear response of the balance elements throughout the load range with only small deviations from a best fit straight line. These deviations are shown in figure 6.

The single-load interactions are plotted in figures 7 through 12 in terms of percent of full-scale output in the element being acted upon versus applied load. Table I shows the magnitude of interactions, at rated loads, of the two-plane balance and similar data for a good commercial floating-frame type balance.

The effect of temperature on sensitivity was determined while the balance was in a heated sleeve. The sensitivity increase due to temperature is approximately 0.02 percent/$^{\circ}$F. This results from uncompensated changes in modulus and gage sensitivity. To determine thermal transient effects, the outer sleeve of the balance was placed in a heat exchanger while the sting end of the balance was maintained at a constant temperature. A thermal transient produced in the heat exchanger caused the outer sleeve of the balance to change temperature according to the curve shown in figure 13. The resulting zero shifts are shown in figure 14. Additional temperature compensation of the gages in the two-plane balance could reduce these effects further. Typical thermal transient errors for commercial floating-frame balances, obtained in the same apparatus, range up to 1 percent of full load.

CONCLUDING REMARKS

General design considerations and performance data have been presented for a modified floating-frame or two-plane balance in which the measuring elements are an integral part of the outer sleeve. This balance provides the linearity, freedom from interaction, and stability generally characteristic of the floating-frame type of balance besides having the following additional advantages:

(1) The hollow inner support is large enough to pass leads through the balance for measuring properties of the model, such as pressures, temperatures, hinge moments, etc.

(2) The balance has maximum stiffness because attachments and flexures have been eliminated.

(3) Thermal expansions produce cancelling errors in the axial-force elements due to the opposite electrical polarity induced by these errors.

(4) The design provides "alinement in construction" as in the compound balance, thereby minimizing stacking tolerances characteristic of the floating-frame balances.

(5) The measuring links are not subject to misalinement under load, thus hysteresis effects, etc., are kept to a minimum.

(6) The machining and fabrication costs are comparable to those of single-piece compound-type balances.

(7) Support redundancy of the system is low, since over 95 percent of the load component to be measured is transmitted through links gaged for the measurement.

(8) Because the limiting element stresses are imposed by combined loads, the loading schedule is flexible; thus normal and side loads or other load combinations can be increased when axial loading is low.

The two-plane configuration has the following disadvantages:

(1) The strain gages must be positioned accurately because the design does not utilize an independent orthogonal set of elements. The stresses due to several load components interact in a single element.

(2) The general arrangement of the balance makes it difficult to apply the concepts to the design of small balances.

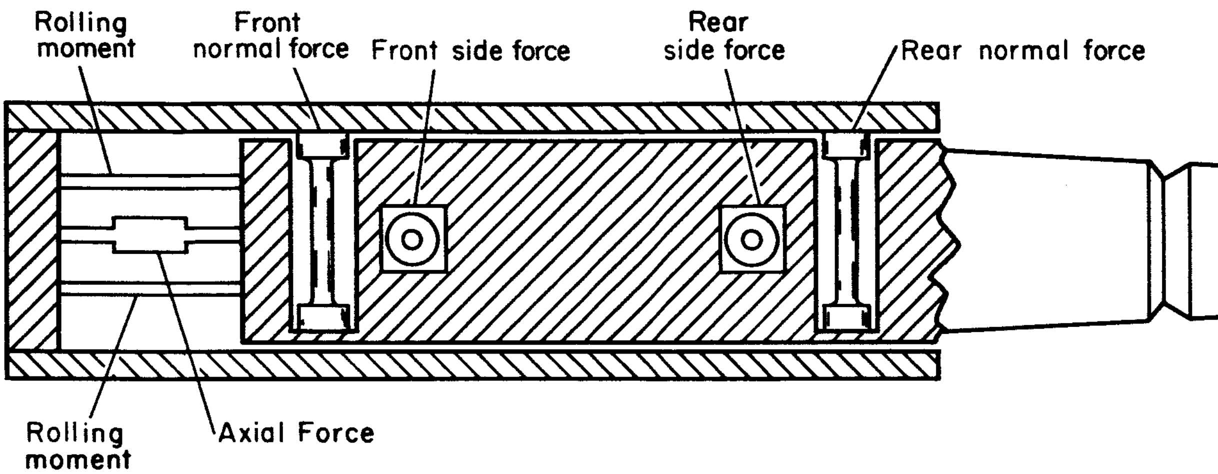
Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., June 15, 1966
125-24-03-05-00

TABLE I.- COMPARATIVE FIRST-ORDER INTERACTION DATA FOR THE AMES TWO-PLANE BALANCE AND A GOOD COMMERCIAL 2.5-INCH BALANCE

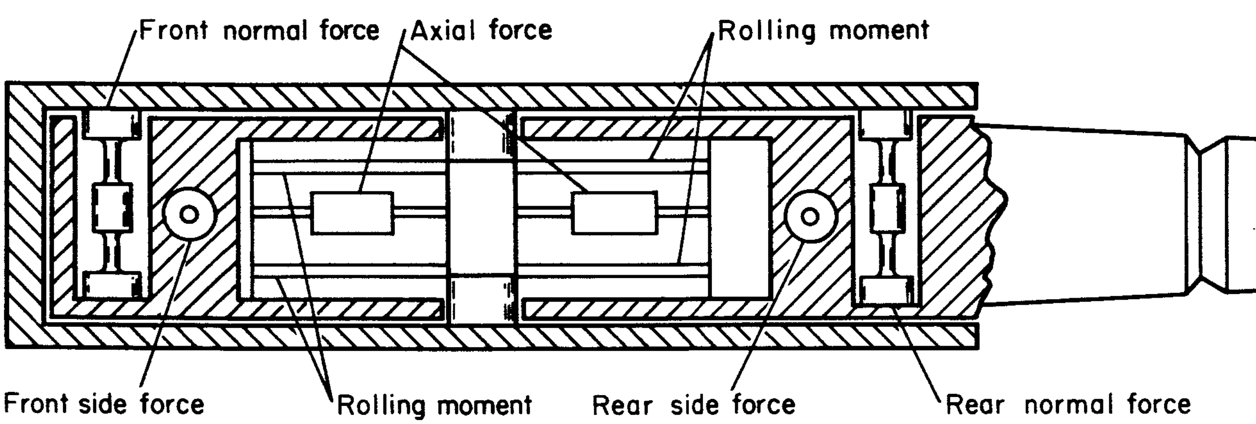
Applied rated load	Interactions, on (percent of full scale): N_F	N_A	S_F	S_A	A	R
N_F		.77 / 1.92	.40 / .35	.22 / .45	1.60 / .72	1.70 / .10
N_A	.22 / .57		.50 / .07	.82 / .37	1.00 / .77	1.48 / .42
S_F	.50 / .10	.97 / .10		.37 / .10	1.30 / .27	2.00 / .60
S_A	.50 / .10	.52 / .17	.37 / .15		1.22 / .30	1.55 / .35
A	.50 / .10	.20 / .10	.15 / .15	.25 / .17		.57 / .32
R	.12 / .15	.05 / .10	.07 / .20	.15 / .10	.52 / .30	

Ames two plane balance → .XX

.XX ← Good commercial balance

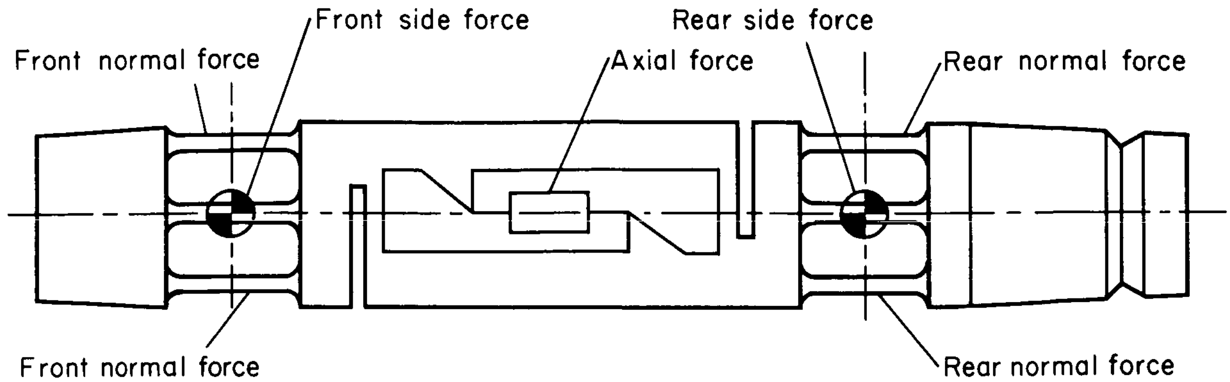


(a) Floating-frame type balance having one station for both the axial force and rolling moment.

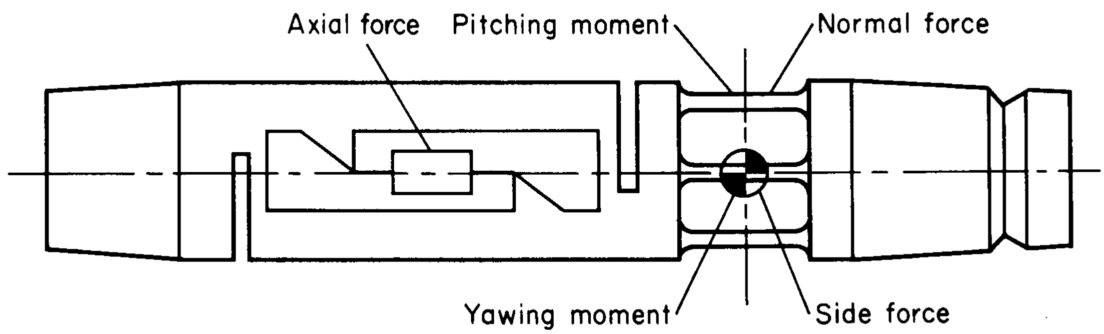


(b) Floating-frame balance modified to provide symmetry for thermal compensation of axial force and rolling moment.

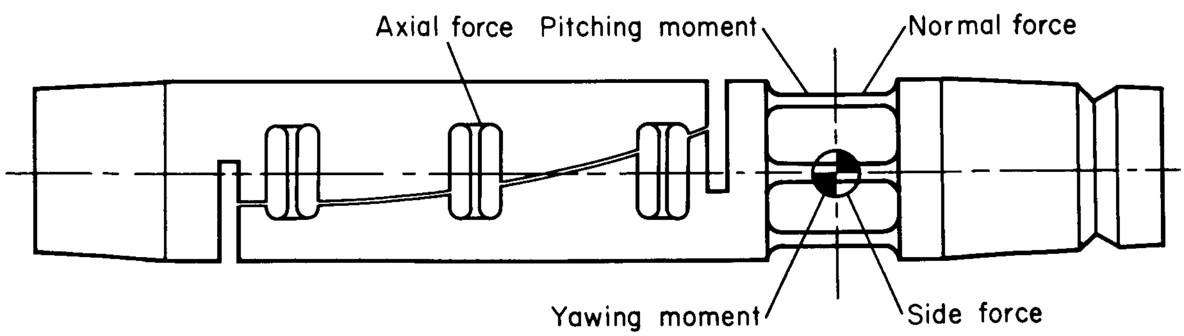
Figure 1.- Schematic drawing of typical floating-frame balances.



(a) Three-section compound balance.



(b) Two-section compound balance.



(c) Two-section compound balance with column stiffeners to reduce interaction loads.

Figure 2.- Schematic drawing of typical compound balances.

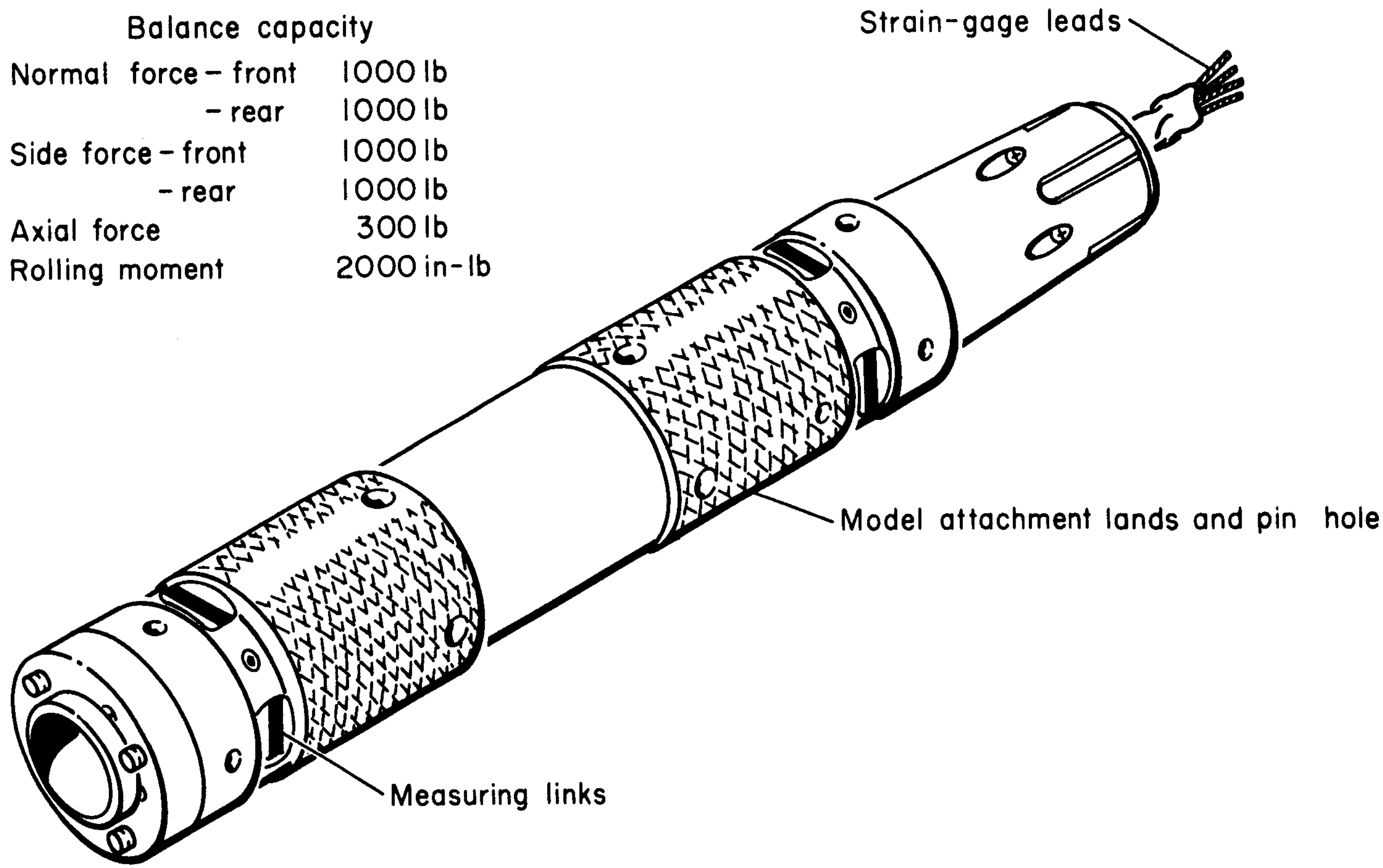


Figure 3.- Sketch of Ames two-plane balance.

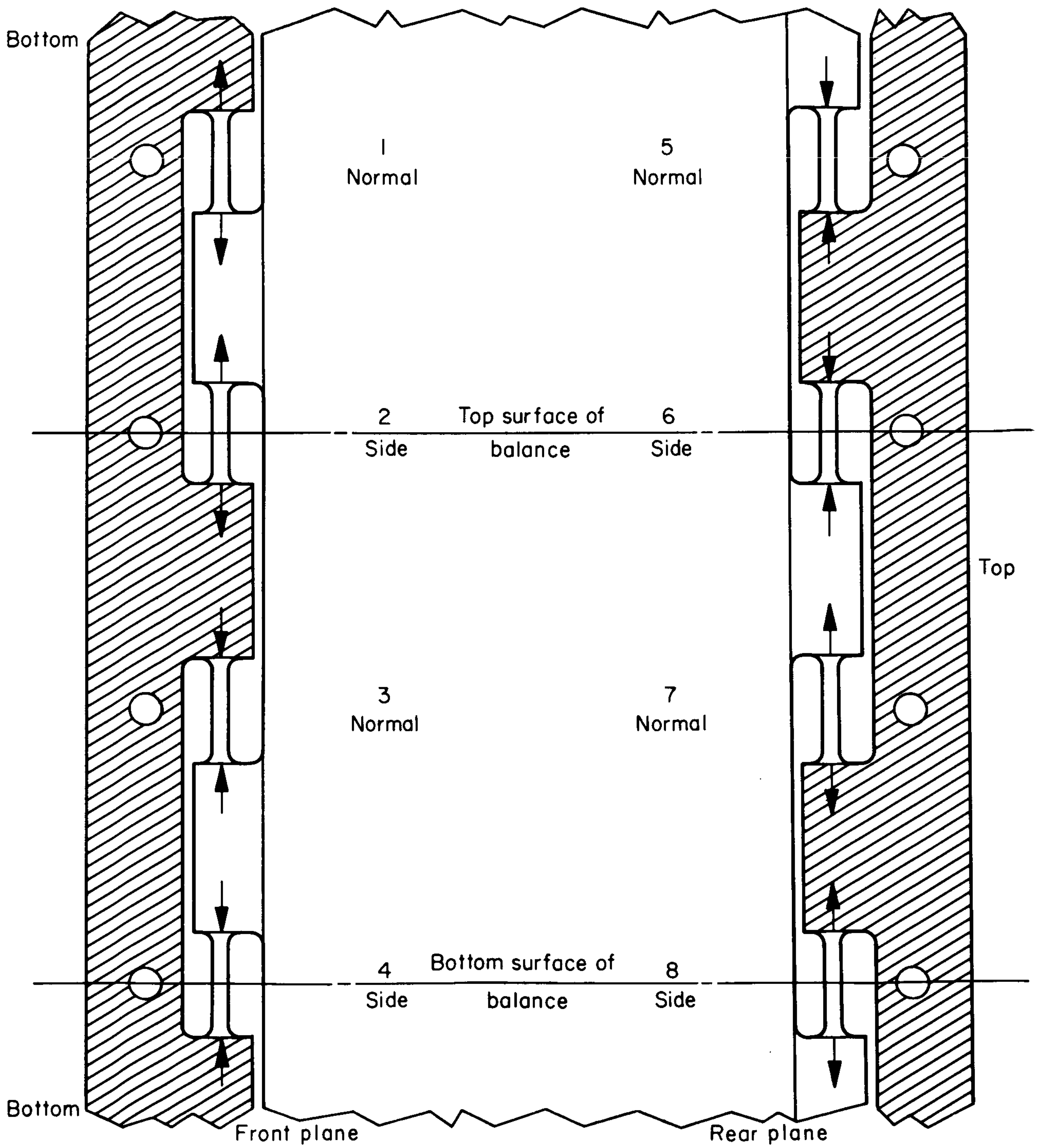


Figure 4.- Developed view of outer sleeve of two-plane balance.

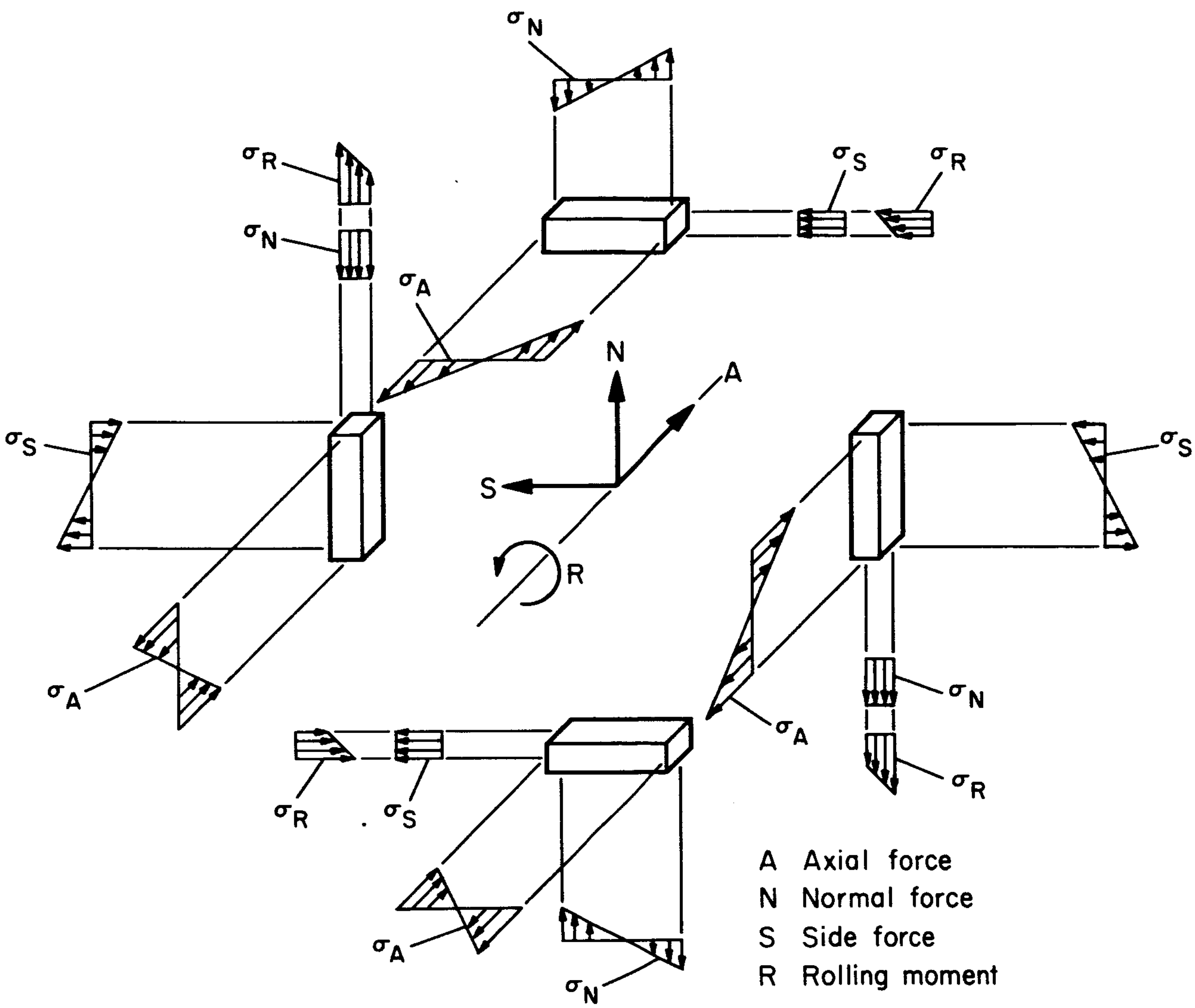
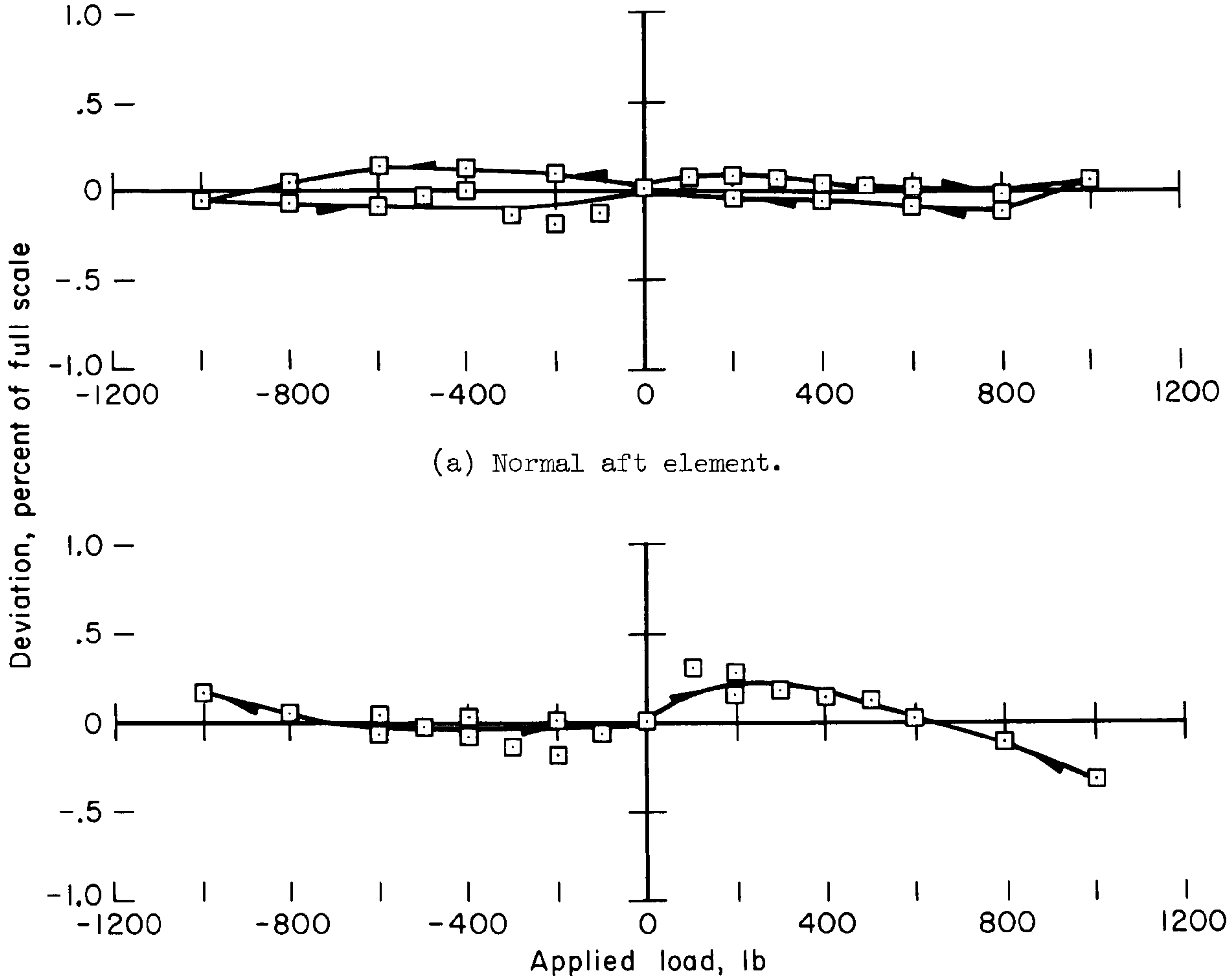


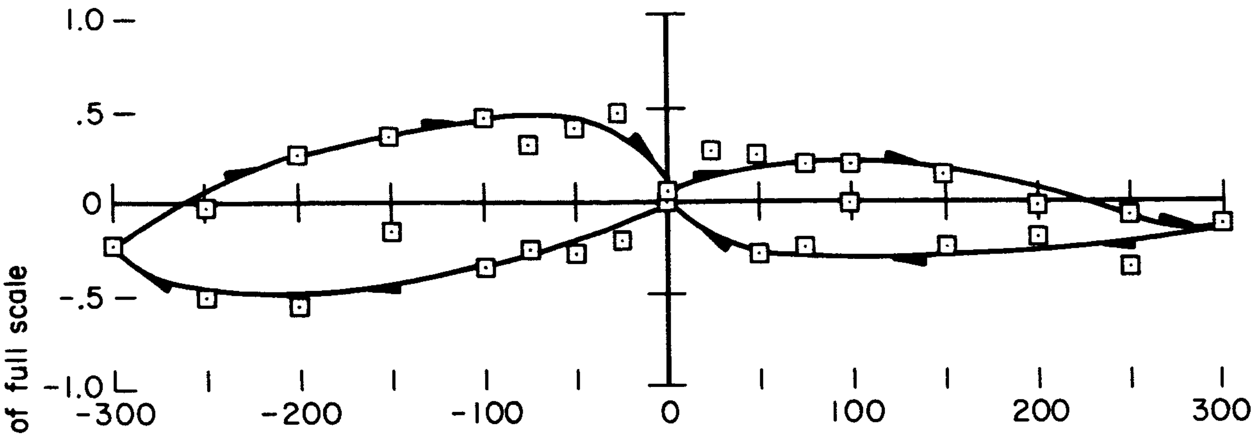
Figure 5.- Stress distribution on front force elements due to positive load configuration.



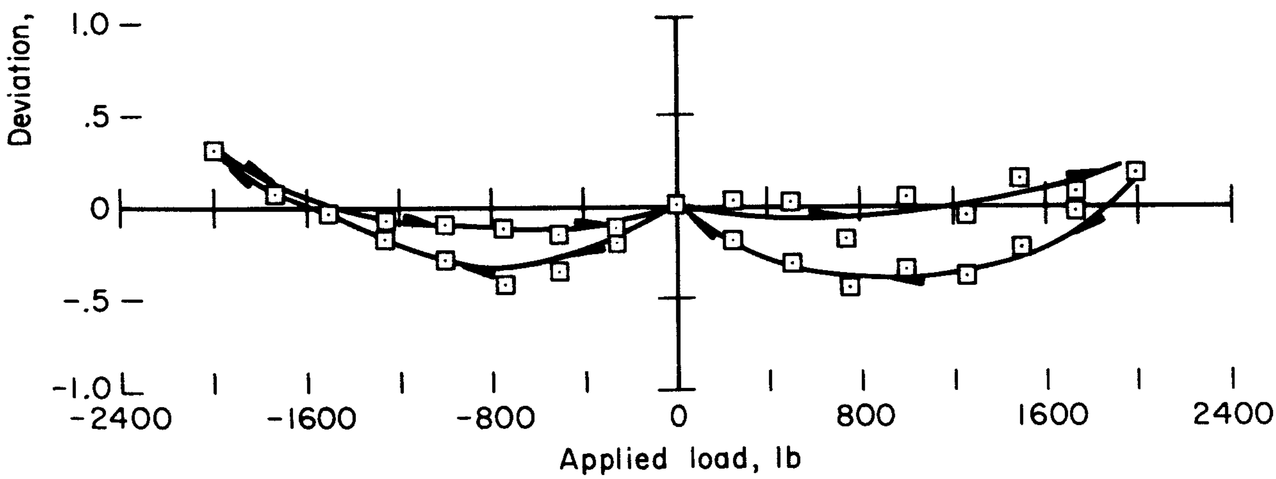
(a) Normal aft element.

(b) Normal front element.

Figure 6.- Hysteresis and linearity.

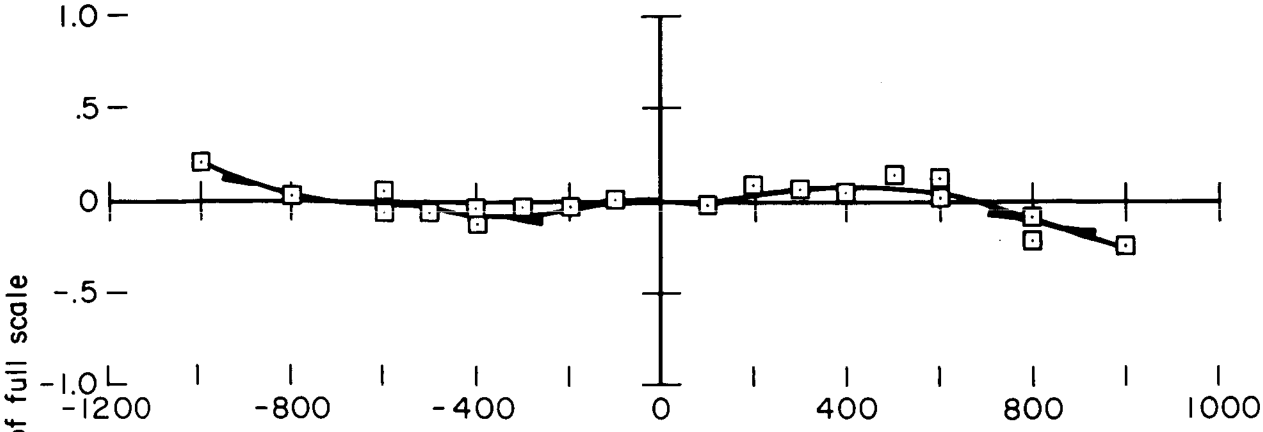


(c) Axial element.

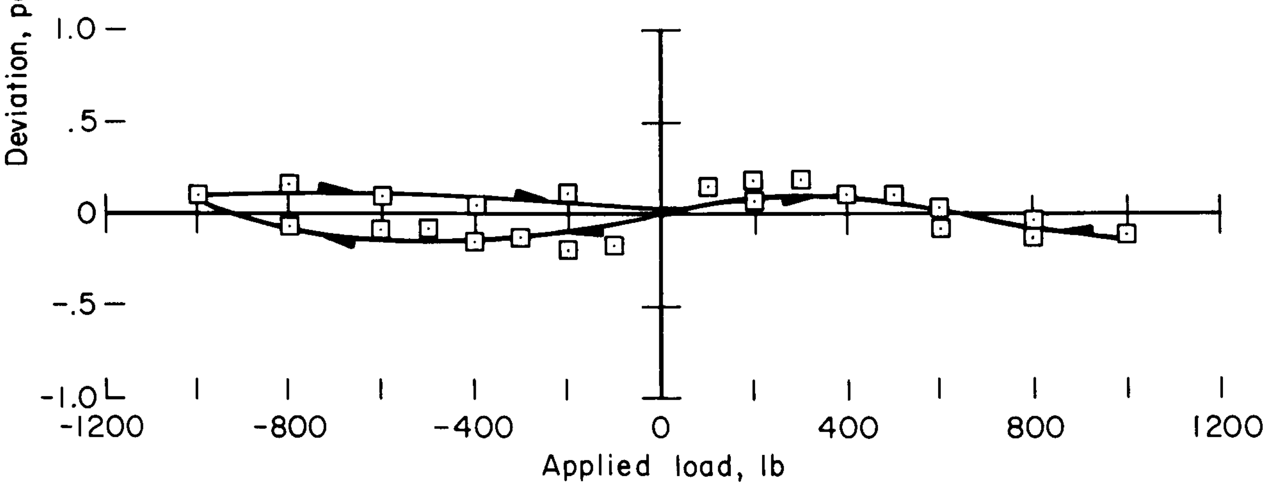


(d) Roll element.

Figure 6.- Continued.



(e) Side front element.



(f) Side aft element.

Figure 6.- Concluded.

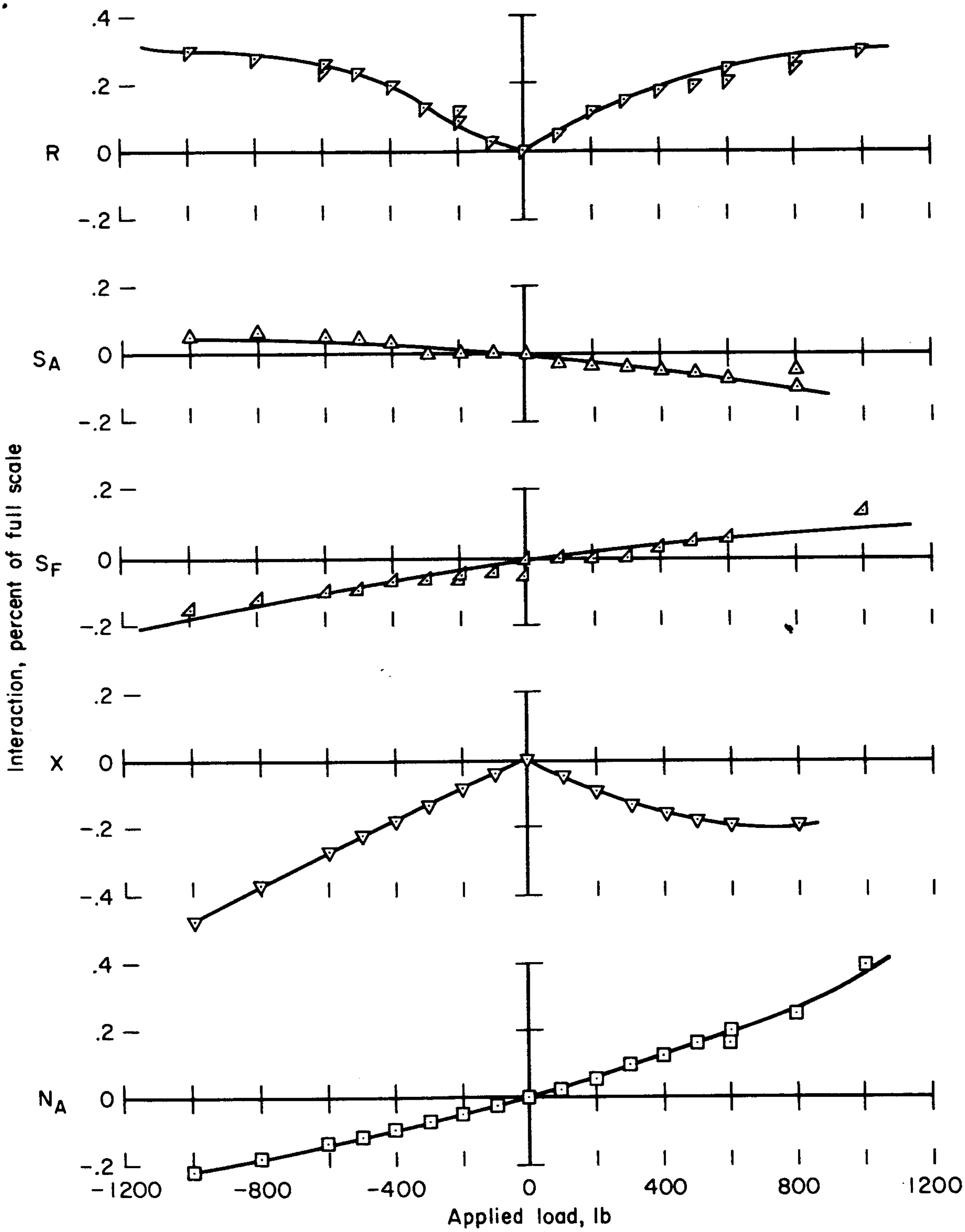


Figure 7.- Interaction due to front normal force (N_F) loading.

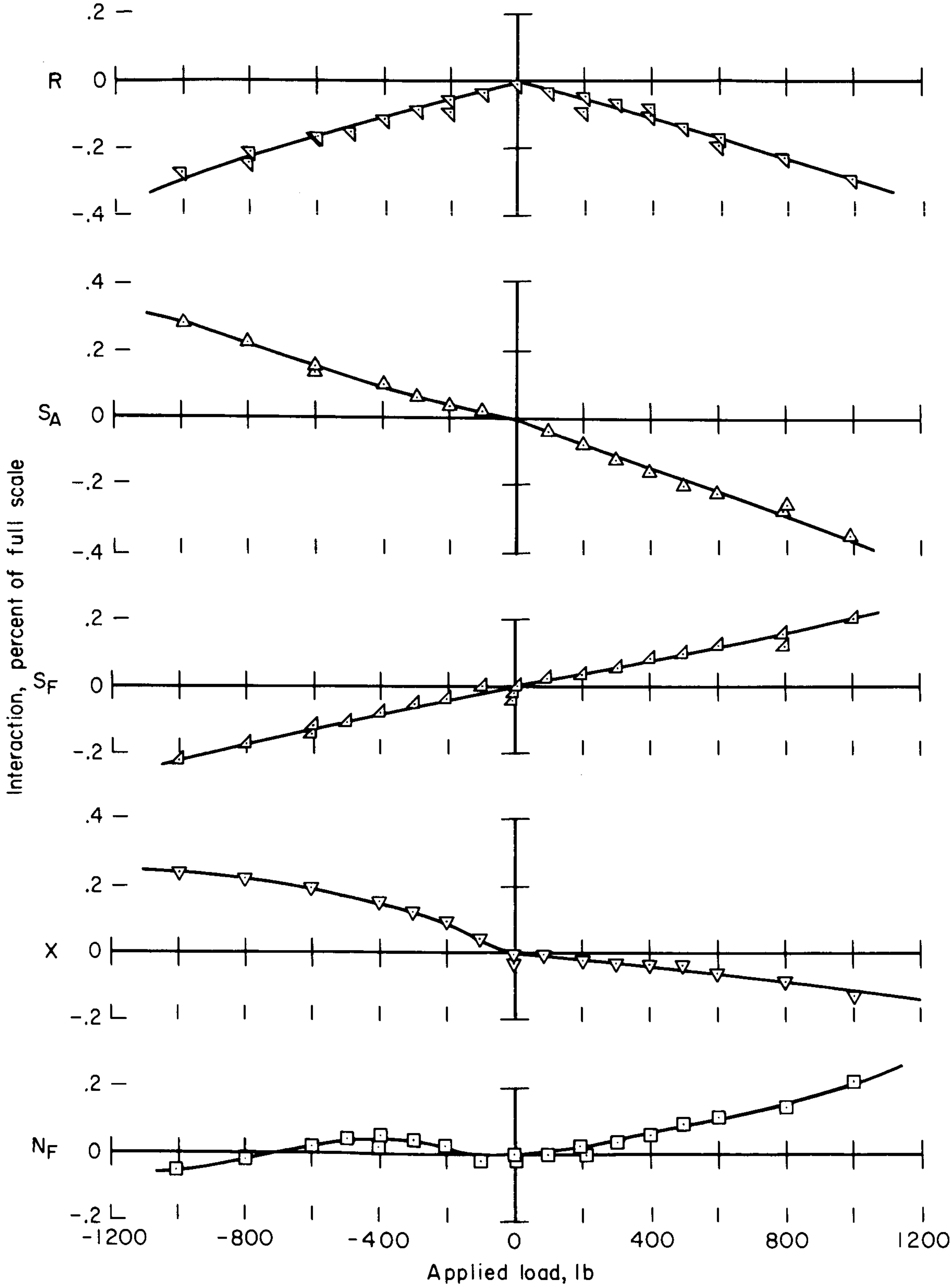


Figure 8.- Interactions due to aft normal force (N_A) loading.

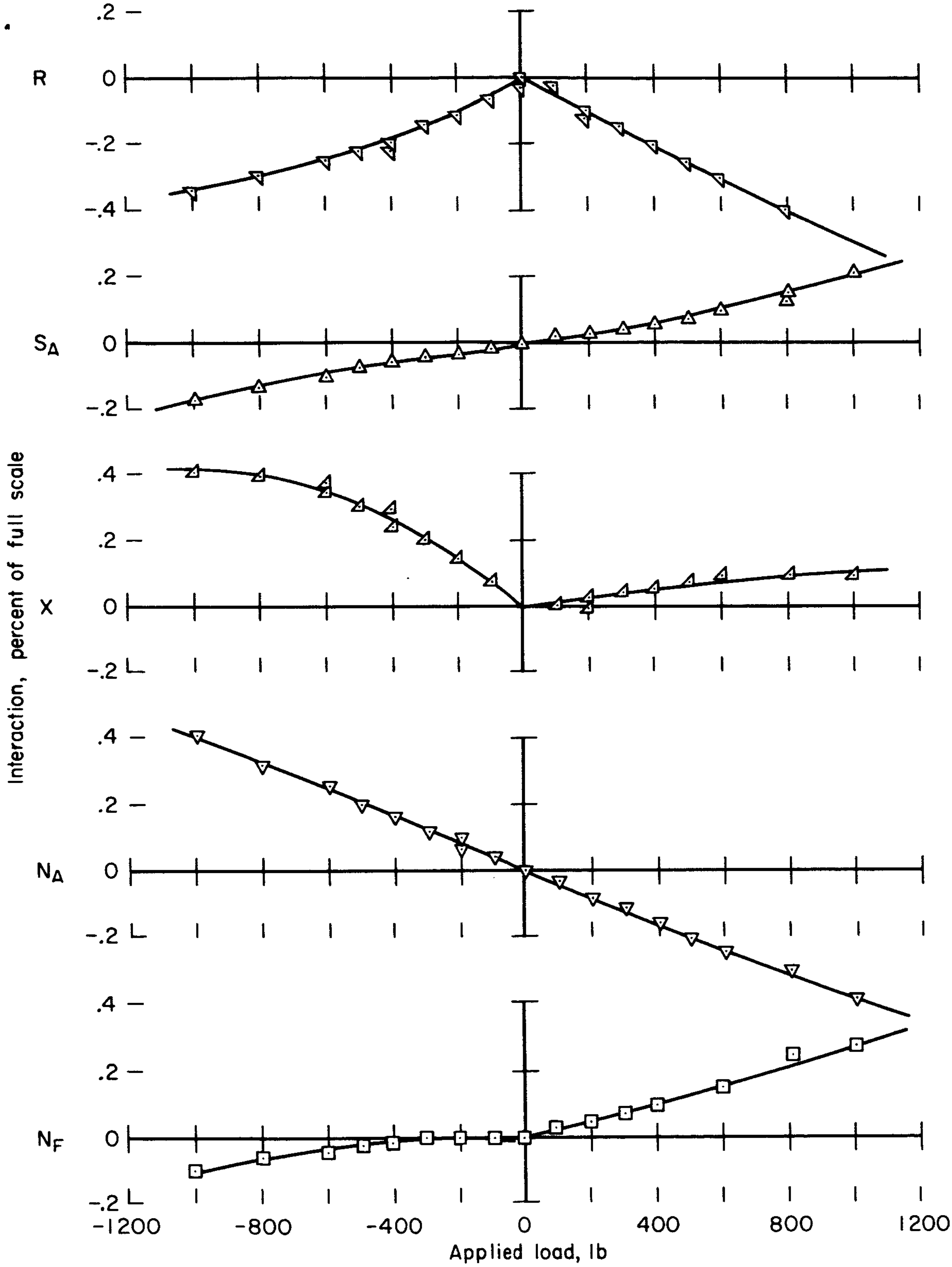


Figure 9.- Interactions due to front side force (S_F) loading.

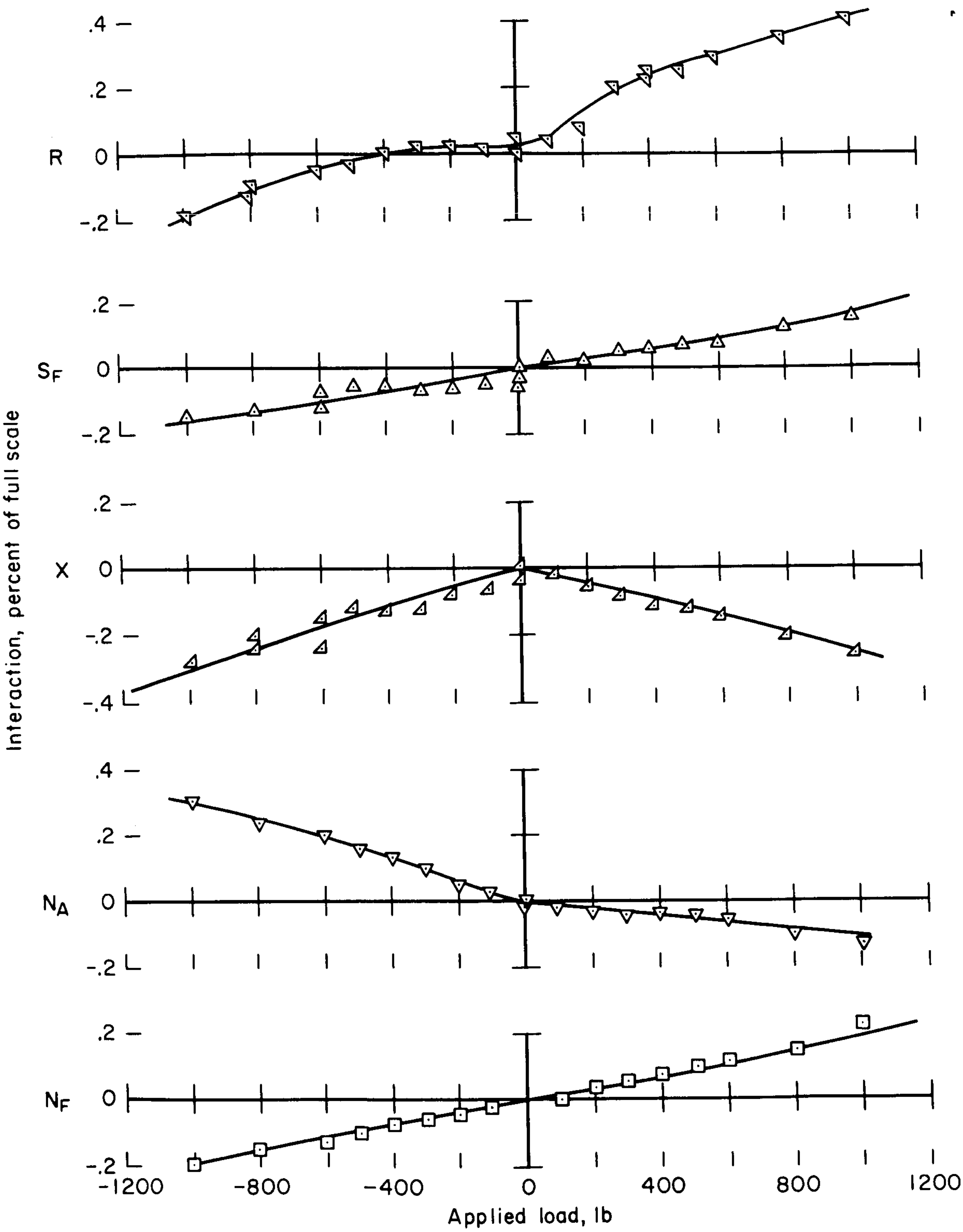


Figure 10.- Interactions due to aft side force (S_A) loading.

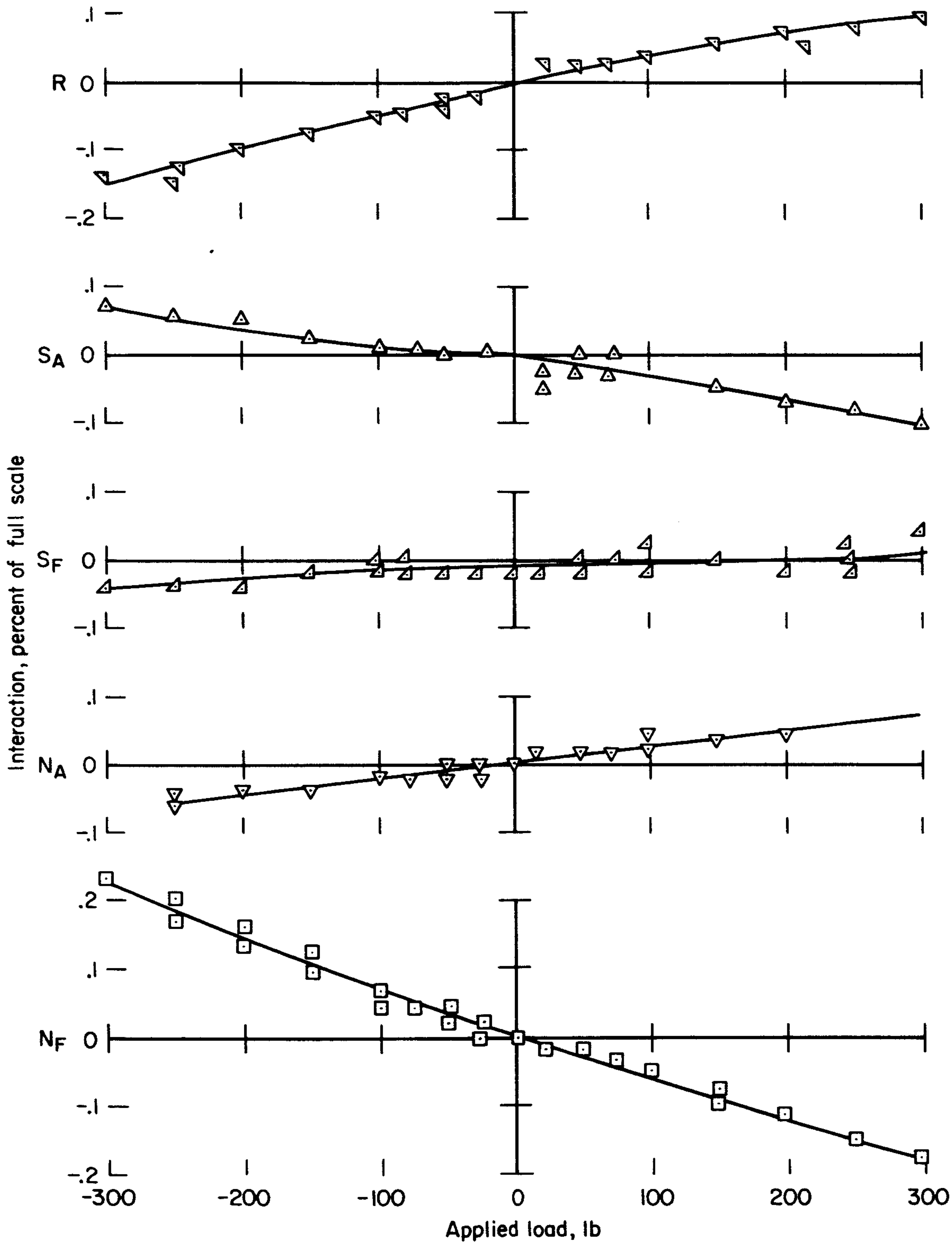


Figure 11.- Interactions due to axial force (A) loading.

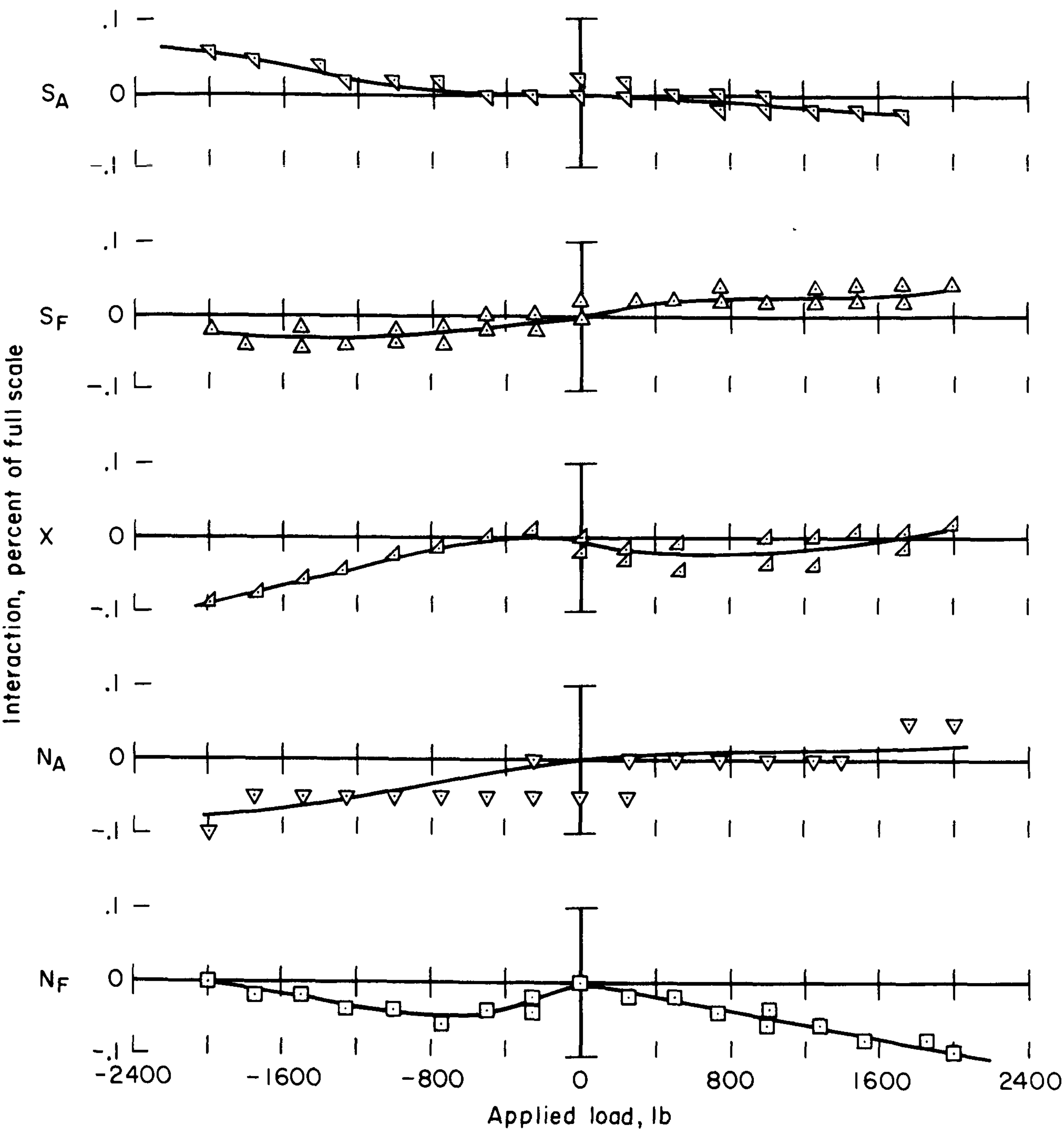


Figure 12.- Interactions due to rolling moment (R) loading.

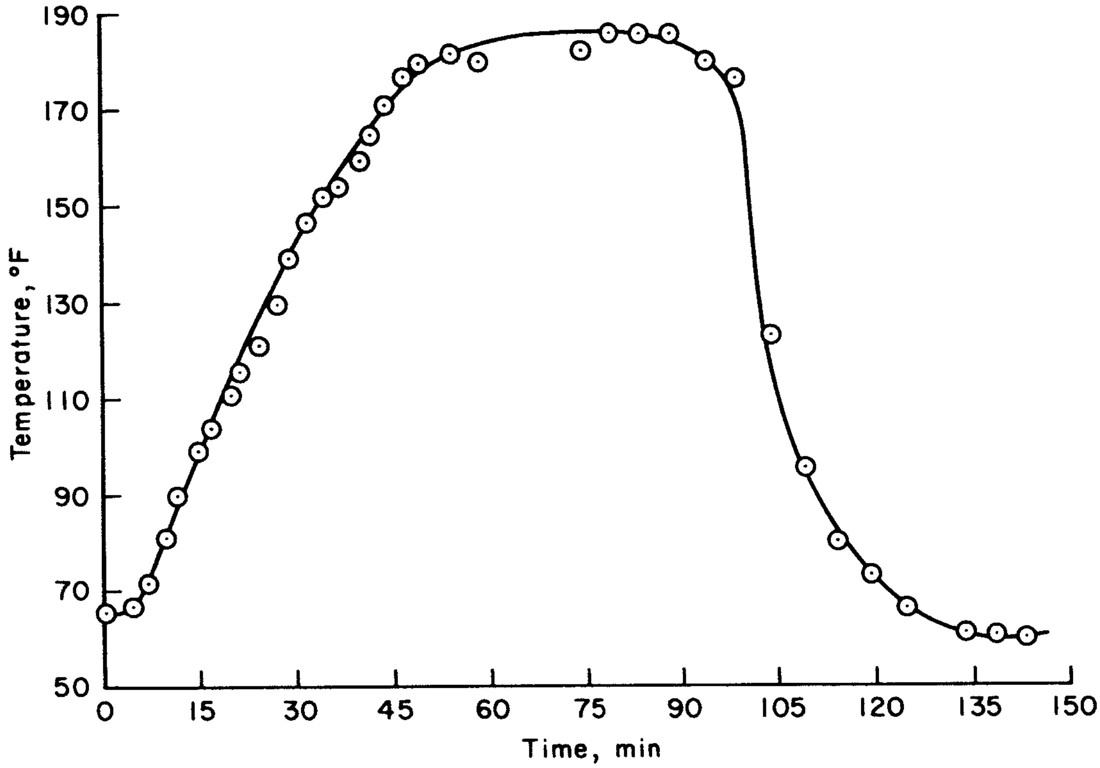


Figure 13.- Thermal transient.

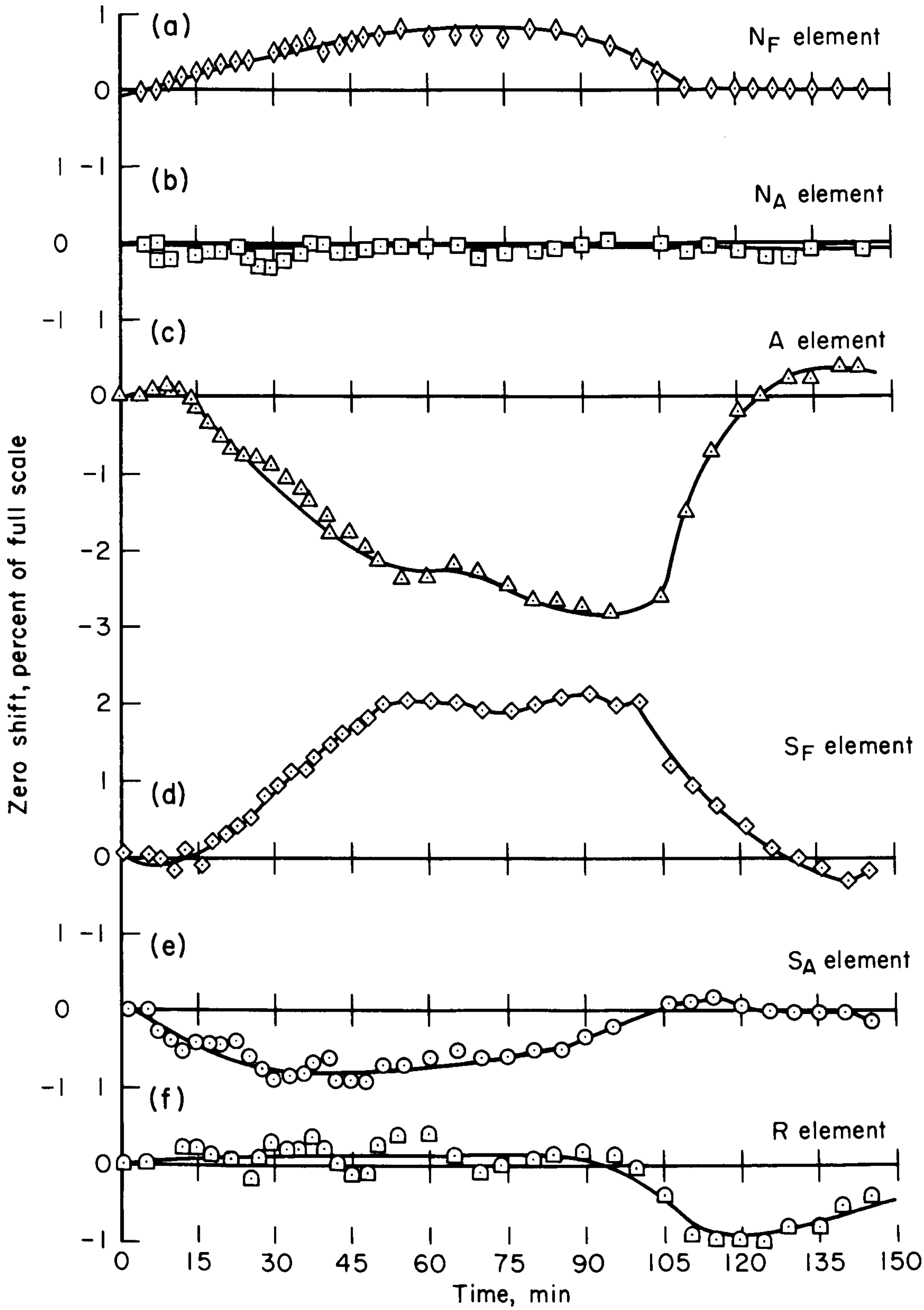


Figure 14.- Zero shifts due to thermal transient.

NASA-Langley, 1966 A-2395